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Overview of NASA Lewis Research Center Free-Piston Stirling Engine Technology Activities Applicable to Space Power Systems

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OVERVIEW OF NASA LEWIS RESEARCH CENTER FREE-PISTON

STIRLING ENGINE TECHNOLOGY ACTIVITIES APPLICABLE TO SPACE POWER SYSTEMS

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SUMMARY

An overview is presented of the National Aeronautics and Space Administration (NASA) Lewis Research Center free-piston Stirling engine activities directed toward space-power application. Free-piston Stirling technology is applicable for both solar and nuclear powered systems. As such, the Lewis Research Center serves as the project office to manage the newly initiated SP-100 Advanced Technology Program. This five-year program provides the technology push for providing significant component and subsystem options for increased efficiency, reliability and survivability, and power output growth at reduced specific mass.

One of the major elements of the program is the development of advanced power conversion concepts of which the Stirling cycle is a viable candidate. Under this program the research findings of the 25 kWe opposed-piston Space Power Demonstrator Engine (SPDE) are presented. Included in the SPDE discussion are initial differences between predicted and experimental power outputs and power output influenced by variations in regenerators.

Projections are made for future space-power requirements over the next few decades. And a cursory comparison is presented showing the mass benefits that a Stirling system has over a Brayton system for the same peak temperature and output power.

The work discussed in this paper is synergistic with the NASA Advanced Solar Dynamic Program where Lewis is conducting research on advanced concentrator, receiver, and thermal energy storage systems at temperatures around 1000 K for Stirling and Brayton cycle power conversions systems.

Introduction

Free-piston Stirling technology was started with the work of William Beale at Ohio University around 1962. This early work resulted in small-scale fractional-horsepower engines which demonstrated basic engine operating principles. The potential advantages (hermetically sealed, high efficiency, and simplicity) of this type of engine became more widely recognized in the early 1970's. This recognition resulted in larger companies taking an interest in its development for heat pumps and solar applications.

Shortly thereafter, the Department of Energy (DOE) took an interest in heat pump development. One area of specific interest to the DOE is the free-piston Stirling engine-driven heat pump. Coincidentally, NASA Lewis was conducting

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research on free-piston Stirling engines as one of several candidates for potential space-power systems. Although both applications, residential heat pumps and space power, appear quite different, their requirements complement each other. These requirements include high efficiency, the potential for long life and high reliability, low vibration, and hermetic sealing. These common requirements became the basis for a cooperative interagency agreement (IAA) between DOE/Oak Ridge National Laboratory (ORNL) and NASA Lewis signed September 1982. The research resulting from this IAA covers generic free-piston Stirling technology applicable to both space power and terrestrial heat pump application. This generic technology effort will not be addressed further as part of this paper due to a length restriction. Reference 1 covers some of the generic work. However, this work is very important to better understand the fundamentals of free-piston Stirling technology.

In addition to the DOE/ORNL - NASA Lewis projects, an interagency agreement has been signed between DOE/Sandia National Laboratory and NASA Lewis to utilize Stirling space technology for solar thermal terrestrial application for generating solar derived electrical power.

And finally, the SP-100 Space Reactor Power Program was established by NASA, the Defense Advanced Research Projects Agency, Department of Energy (DOE) and the Air Force in February 1983. For almost three years various power conversion concepts were investigated, until recently, when the thermoelectric concept was chosen for development and ground testing to be conducted until 1991. This SP-100 program is now in the first year of a 5-yr phase II Ground Engineering System (GES) program. In support of this program, free-piston Stirling system technology development is continuing under the newly initiated SP-100 Advanced Technology Program. The Lewis Research Center serves as the project office for NASA's SP-100 Advanced Technology Program, the purpose of which is to demonstrate the technology necessary to proceed into final development of a space-qualified free-piston Stirling engine to meet future mission needs. The free-piston Stirling advanced technology work described in this report is either conducted at or managed by the Lewis Research Center in support of the NASA SP-100 Advanced Technology Program.

Why Free Piston?

The Stirling free-piston system has many attractive attributes, several of which are tabulated in Fig. 1. Specifically, the Stirling cycle is the most efficient thermodynamic heat engine cycle that exists. Of the concepts considered for SP-100 selection, the Stirling cycle has the highest efficiency for the same given heat input and heat rejection temperatures. Because the Stirling system employs the gas bearing - either hydrodynamic or hydrostatic - there is the potential for long life and high reliability.

A system composed of a Stirling engine/linear alternator has only two moving parts per cylinder - that is the displacer and the power piston/alternator plunger. The result is a relatively simple configuration. A single-cylinder engine can be balanced either actively or passively using a spring-mass combination.

Free-piston Stirling engines contain no sliding rod seals such as those present in the kinematic concepts. The energy conserved by not having to overcome the losses in the frictional rod seals is not totally free. The free-piston Stirling concept utilizes gas springs which have hysteresis losses. At the present time, it is not known whether the free-piston concept or the kinematic concept is the most efficient, but it is felt that there should not be much difference between the efficiencies of the two concepts. The fact that there is no oil inside the engine makes the free-piston a strong candidate for long life. There is no chance of getting oil contamination into the regenerator and degrading engine performance. An opposed-piston free-piston Stirling engine with a common expansion space, theoretically has the potential for graceful degradation in the event that one engine has larger losses than the other. Both pistons then produce equal power, but at a reduced level.

The power output of the free-piston is very flexible in that not only is a linear alternator possible, but so are other concepts. These concepts include the hydraulic output with a hydraulic motor/pump and a conventional rotating alternator; and a hydraulic drive/gas compressor output which can provide gas turbine power to a conventional or high speed alternator.

Stirling/Brayton System Mass Comparisons

Reference 2 has assembled information from various Lewis Research Center conducted dynamic space power systems analyses. The study was to compare the different nuclear and solar dynamic power system technologies on the basis of system mass and drag area with emphasis on the growth space station application. The comparisons presented here, which will show only the mass variation, are considered preliminary, in that results can be expected to change as assumptions and analyses are refined and as different tradeoffs are examined. However, it is believed that the relative comparisons are basically valid. It is clear that other system characteristics such as cost, reliability, development status and safety will greatly impact additional comparisons. For the purpose of the study a 40 kWe solar dynamic system module size was assumed, with four modules producing 160 kWe. Each module is a self-contained power system consisting of a solar collector, heat receiver, power conversion system (including engine and energy storage), power system radiator, and power conditioning system. In the solar study the heat storage media is either LiF or LiOH.

The nuclear dynamic systems consist of a single liquid-metal cooled reactor, a man-rated radiation shield, multiple Brayton or Stirling engines (for redundancy), power systems radiators, and power conditioning. The nuclear reactor is assumed to be 30 m from the space station habitat. Figure 2 shows total system mass for both Brayton and Stirling systems each using solar and nuclear energy sources, as a function of electrical outlet power. The solar power systems are assumed to scale linearly with power, while the nuclear power systems scale less than linearly. In all cases the Stirling system, because of its high efficiency, is the lighter system.

Future Space Power Projections

Over the next several decades, the amount of electric power required in space is expected to grow immensely. Today's larger satellites require almost 10 kWe of power. Most of these satellites are powered by solar arrays with storage batteries. Tomorrow's space platforms will continuously require hundreds of kilowatts; and some will periodically consume many megawatt-hours of energy. These space platforms will include manned space stations, communication stations, surveillance platforms, and defensive weapons. These large power systems will be quite different from today's solar arrays.

Projections of space power growth tend to show broad trends as shown in Fig. 3. These broad trends are a direct result of uncertainties in future mission capabilities and needs. It is however, clear that future space power needs may be several orders of magnitude greater than anything that has been accomplished to date. The challenge for the space power planner is formidable - to select power technologies that can meet the projected trends and adapt to multiple users. One potential solution is the use of dynamic power conversion units - either solar or nuclear.

Figure 4 is an artist's conception of an SP-100 Stirling engine system. The concept uses a nuclear reactor and shield along with both fixed and deployed radiator panels. Thermoelectric electromagnetic pumps are employed to transport the hot liquid from the reactor to the Stirling engines.

Space Power Demonstrator Engine (SPDE)

NASA, in coordination with the overall SP-100 development program, initiated an SP-100 Advanced Technology Program. The objectives of the Advanced Technology program are to augment the ground engineering system (GES) engineering development and ground testing of major subsystems and to provide significant component and subsystem options for increased efficiency, reliability, survivability, and growth, at reduced weight and high reliability. Thus, enhancing the chances of success for the overall SP-100 power system development.

These goals will be obtained through the key elements of the broadly based program which include: systems analysis to guide the overall effort and advanced technology development in the areas of Energy Conversion, Thermal Management, Power Conditioning and Control, Space Power Materials and Structures, and Spacecraft Environmental Effects. Building upon the technology advancements accomplished in Phase I of the SP-100 program, the advanced Stirling technology conversion project is one important element of the program. The key Stirling technology areas needed for this broadly based program are listed in Fig. 5.

In concert with the Advanced Technology Program a demonstrator engine was built and is currently under test. The engine is called the Space Power Demonstrator Engine (SPDE). The SPDE was designed and fabricated by Mechanical Technology Inc. (MTI) of Latham, NY. The engine is currently under test at this facility. The nominal design was 25 kWe from the two opposed-piston Stirling engine - linear alternator system. A photograph of the engine is shown in Fig. 6. The engine is about 1-1/4 m in length and about 1/3 m in diameter. It is suspended from the ceiling by four vertical straps. This flexible suspension was the test configuration and no discernible vibration was observed during operation. Accelerometers mounted on the engine housing indicated maximum amplitudes (peak-to-peak) of less than 0.01 mm which corresponds to a "g" of less than 0.2. A general description of the engine is given in Refs. 3 and 4.

Because of the tight schedule to design, fabricate, and test the engine, the maximum engine temperature for initial testing was limited to 650 K. The cost of a liquid metal facility (necessary for higher temperature operation) was also a factor in selecting 650 K as the heater temperature. The cold or cooler temperature was maintained at 325 K in order to operate the engine at a temperature ratio of 2. The temperature ratio of 2 was chosen for a minimum weight system (including reactor and radiator).

The SPDE is a development engine and, as such, is not a final space configuration. However, with straight-forward material substitutions and replacing bolts and flanges with welds, the SPDE specific mass at design power is reduced to 7.2 kg/kWe from the laboratory specific mass of 12.7 kg/kWe.

The two top and bottom curves of Fig. 7 compare the predicted and early (11-22-85) experimental results at design pressure of 150 bar. The engine ran well but the power generated was about half the predicted power. This was unexpected because at the half design pressure of 75 bar the experimental power was about 90 percent of the predicted power. Keep in mind that the engine frequency also changes with engine pressure. At 75 bar the engine frequency is 74 hz and at 150 bar the frequency is 105 hz. A concentrated effort was conducted by both MTI and NASA to resolve the power shortfall problem. On balance, the mechanical operation of the engine has been flawless. Both power pistons (alternator plungers) and one displacer have been completely trouble-free. One displacer drive was troublesome until a positive cylinder alignment was incorporated into the design. In order to understand why there was a power shortfall additional instrumentation was added to the engine as well as a complete recalibration of all flow meters, resistance temperature devices, and pressure sensing devices. Thermocouples were located at the interface of each heat exchanger (i.e., heater-regenerator, regenerator-cooler, etc.).

A series of diagnostic tests were conducted in order to isolate potential power shortfalls. The tests consisted of cold and at temperature motoring tests with the displacer (one of the two moving parts per engine) locked in place. A motor-generator set supplied power to motor the alternator of the SPDE. The purpose of these tests was to determine whether gas leakage and/or hysteresis are a cause of the power shortfall. Additional motoring tests were conducted with both displacer and piston unlocked at a temperature ratio of 1. This test verified that leakage and/or hysteresis were not contributing to the power shortfall.

The SPDE engine is at the forefront of Stirling technology and operates at 105 Hz, 1.75 times greater than previously designed Stirling engines (the equivalent to an automobile engine at 6300 rpm). As such, the higher frequency generates large dynamic oscillating forces on the regenerator which have resulted in regenerator fretting and damage. Previous free-piston Stirling regenerators - due to the low pressure ratio of free-piston engines - were not sintered or canned and maintained their integrity over long periods of operation.

As an example, the nominal 3 kW MTI Endurance Engine ran over 5500 hr without any regenerator problems. Nevertheless, Fig. 8 shows a comparison between the uncanned, unsintered screen regenerators before testing and after only about 20 hr of 105 Hz operation. Sintered and canned regenerators are on order for future testing.

The damaged screen regenerators were replaced with a sintered - though not optimized - regenerator of a smaller diameter wire and higher porosity. Also a modification was made to an element of the load circuit which previously prevented achievement of power levels greater than about 14 kW. Although the regenerator was not optimum the performance improvement was dramatic. This can be seen by the middle curve in Fig. 7. The final testing is far from complete but further power improvement is expected when the sintered screen regenerators are installed. At present, the alternator is not performing as expected and we plan a detailed investigation in this area.

Concluding Remarks

The space power demonstrator engine (SPDE) has successfully operated for over 300 hr and has delivered 20 kW of PV power to the alternator plunger. The SPDE has demonstrated that a dynamic power conversion system can, with proper design, be balanced; and the engine performed well with externally pumped hydrostatic gas bearings. Testing of the engine will continue its steady development and will provide a test bed to evaluate new and unproven components/technologies.

In conclusion, we feel that the free-piston Stirling engines are just starting to achieve the attention and creditability that they deserve for space-power application. Free-piston Stirling systems can easily be used with both solar and nuclear powered systems and offer the potential for high efficiency, long life and high reliability.

Acknowledgments

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The SPDE engine testing is being conducted by Mechanical Technology Inc., Latham, N.Y. under the direction of Mr. George Dochat. The NASA project manager is Mr. Donald L. Alger of the NASA Lewis Research Center.

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- HIGH EFFICIENCY (RELATIVE TO OTHER SYSTEMS)
- POTENTIAL FOR LONG LIFE AND HIGH RELIABILITY
- NON-CONTACTING GAS BEARINGS
- TWO MOVING PARTS
- DYNAMICALLY BALANCED
- NO ROD SEALS
- NO OIL INSIDE ENGINE
- POTENTIAL FOR GRACEFUL DEGRADATION
- POWER OUTPUT FLEXIBILITY

FIGURE 1.- WHY FREE-PISTON STIRLING?

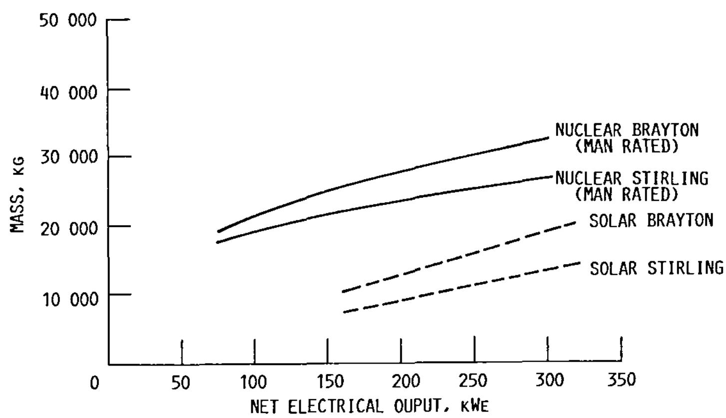


FIGURE 2.- TOTAL SYSTEM MASS FOR POTENTIAL SPACE STATION POWER SYSTEMS.

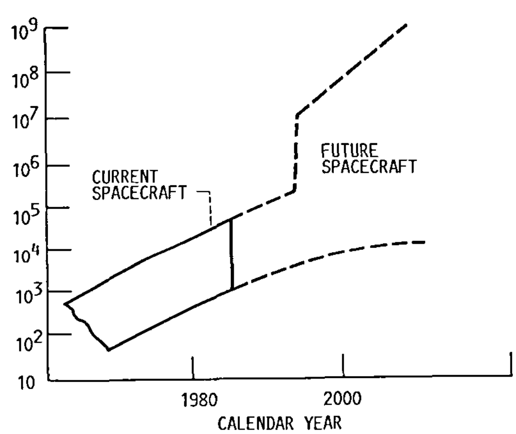


FIGURE 3.- PLANNED SPACE POWER PROGRAMS ADDRESS SPACECRAFT GROWTH.

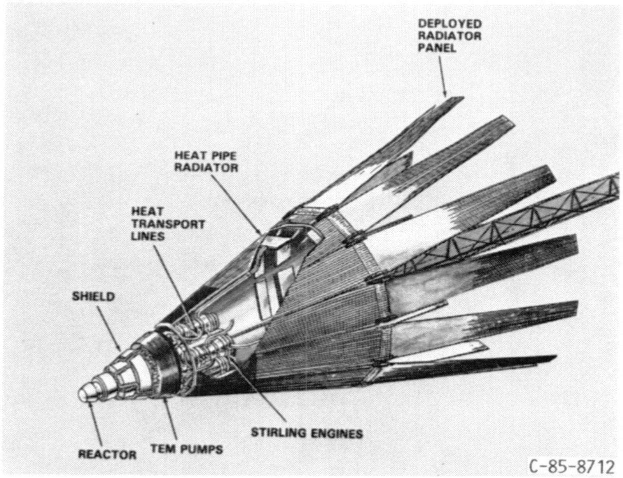


FIGURE 4. - ARTIST'S CONCEPTION OF SP-100 STIRLING SYSTEM.

- IS A LONG RANGE BROADLY BASED PROGRAM
- SUPPORTS KEY STIRLING TECHNOLOGY AREAS NEEDED FOR:
  - GAS BEARINGS
  - LINEAR ALTERNATORS
  - HEAT EXCHANGERS
  - MATERIALS
  - POWER CONDITIONING INTERFACE
  - OSCILLATING FLOW
  - PERFORMANCE PREDICTIONS

FIGURE 5.- NASA SP-100 ADVANCED TECHNOLOGY PROGRAM.

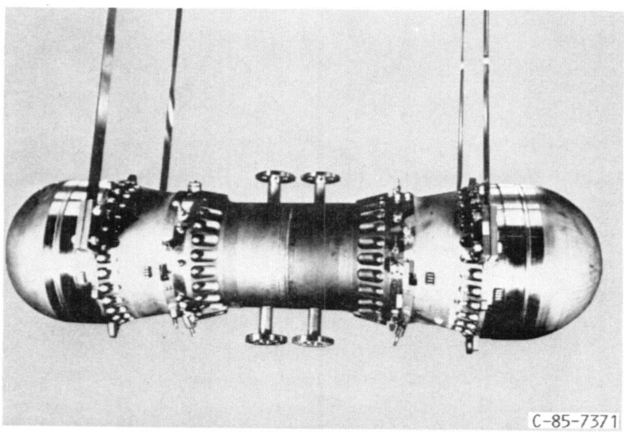


FIGURE 6. - 25 kWe SPACE POWER DEMONSTRATOR ENGINE (SPDE) AT MECHANICAL TECHNOLOGY INC.

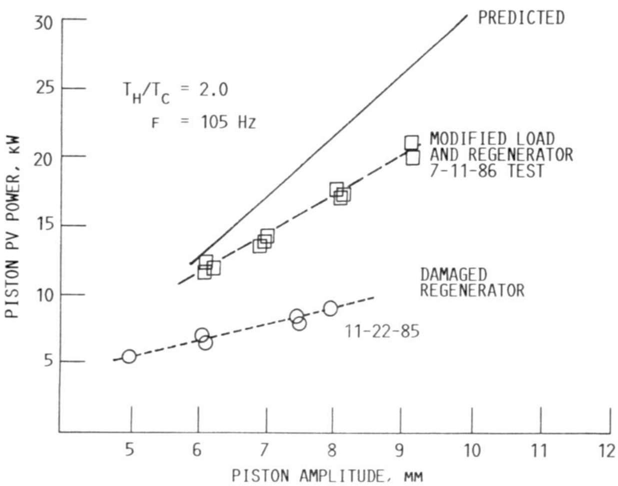
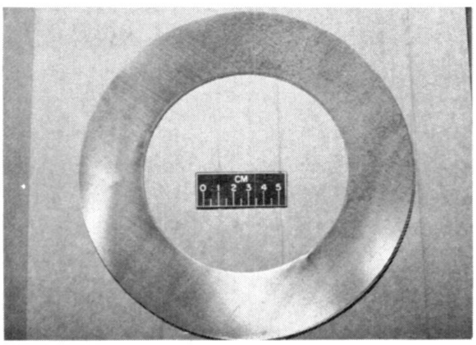
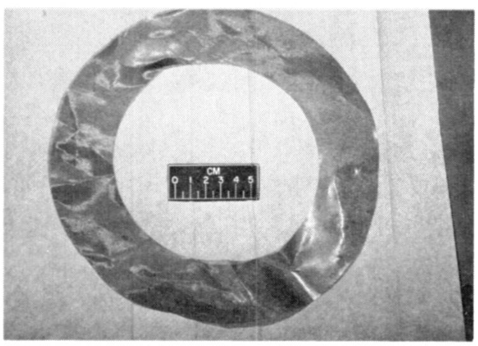


FIGURE 7.- SPDE PV POWER AT 150 BAR.



BEFORE 105 Hz OPERATION



AFTER 20 HR OF 105 Hz OPERATION

FIGURE 8. - COMPARISON OF SCREEN REGENERATORS.

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16. Abstract

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